

CLAIMS

What is claimed is:

1. A method of laser induced breakdown of a material comprising:
 - (a) depositing energy within a material to extract electrons from a valence band providing unbound electrons at a density sufficient to define a first absorption volume, with the electron density being lower at the periphery of said first absorption volume and higher at one or more select regions inward of said periphery of said first absorption volume; and
 - (b) depositing added energy within the first absorption volume, preferentially at each said select region causing contraction of said first absorption volume to a smaller second absorption volume corresponding to said one or more select regions, thereby causing damage of material selectively within said second absorption volume essentially without collateral damage to the balance of material in said first absorption volume.
2. The method of Claim 1 wherein said added energy is preferentially deposited at a plurality of said select regions, thereby causing selectively damaged material at each of said select regions, said selectively damaged material constituting said second absorption volume.

3. The method of Claim 1 wherein said added energy is preferentially deposited at a single select region, thereby causing selectively damaged material within said second absorption volume defined by said single select region.

4. The method of Claim 1 wherein said depositing of added energy at each said select region causes reduced penetration depth in said material along an optical path as compared to the penetration depth in said material adjacent said select region.

5. The method of Claim 1 wherein said added energy is optical energy deposited at each said select region to a penetration depth sufficient to cause electron density of $10^{23}/\text{cm}^3$.

6. The method of Claim 5 wherein the penetration depth is in a direction along a path of said optical energy in said material.

7. The method of Claim 1 wherein said added energy is optical energy deposited at each said select region to a penetration depth sufficient to cause electron density of density of at least $10^{19}/\text{cm}^3$.

8. The method of Claim 1 wherein said added energy is optical energy deposited at each said select region to a penetration depth sufficient to cause electron density of greater than $10^{19}/\text{cm}^3$.

9. The method of Claim 1 wherein said added energy is optical energy deposited at each said select region to a penetration depth sufficient to cause electron density in a range of $10^{19}/\text{cm}^3$ to $10^{23}/\text{cm}^3$.

10. The method of Claim 1 wherein the added energy generates further unbound electrons.

11. The method of Claim 1 wherein several different foci correspond to respective said select regions.

12. The method of Claim 1 wherein the source of energy in steps (a) and (b) is a single pulse of optical energy having modulated intensity profile.

13. The method of Claim 1 wherein the deposition of energy in steps (a) and (b) is by a single pulse of optical energy, said single pulse having a first portion depositing energy sufficient to cause unbound electrons in the first absorption volume and a second portion of the single pulse depositing energy in said one or more select regions to cause damage.

14. The method of Claim 1 wherein the added energy of step (b) is at an intensity that is the same or different from the intensity of step (a).

15. The method of Claim 1 wherein a penetration depth of deposited optical energy is smaller than the wavelength of the optical energy.

16. The method of Claim 1 wherein each said select region is essentially defined by a penetration depth in a Z axis direction less than a dimension in the X-Y axis plane of a spot of the deposited energy.

17. The method of Claim 1 wherein said damage of material comprises damage at a surface of the material.

18. The method of Claim 1 wherein said damage of material comprises damage below the surface of the material.

19. A method of laser induced breakdown of a material comprising:

(a) depositing energy within a material to extract electrons from a valence band providing unbound electrons with an electron density being higher at one or more select locations of a first absorption volume as compared to one or more non-select locations of said first absorption volume; and

(b) depositing added energy within the first absorption volume, preferentially at each said select location causing contraction of said first absorption volume to a smaller second absorption volume defined by one or more regions of the material corresponding to respective said one or more select locations, thereby causing damage of material selectively within said second absorption volume, essentially without collateral damage to the balance of material in said first absorption volume.

20. The method of Claim 19 wherein said added energy is preferentially deposited at a plurality of said select locations, thereby causing selective damage of material at each of said interior regions collectively defining said second absorption volume.

21. The method of Claim 19 wherein said added energy is preferentially deposited at a single select location, thereby causing select damage of material within said second absorption volume corresponding to said single interior region.

22. The method of Claim 19 wherein said depositing of added energy at each said select region causes reduced penetration depth in said material along an optical path as compared to the penetration depth in said material adjacent said select region.

23. The method of Claim 19 wherein said added energy is optical energy deposited at each said select location to a penetration depth sufficient to cause electron density of $10^{23}/\text{cm}^3$.

24. The method of Claim 23 wherein the penetration depth is in a direction along a path of said optical energy in said material.

25. The method of Claim 19 wherein said added energy is optical energy deposited at each said select location to a penetration depth sufficient to cause electron density of at least $10^{19}/\text{cm}^3$.

26. The method of Claim 19 wherein said added energy is optical energy deposited at each said select location to a penetration depth sufficient to cause electron density of greater than $10^{19}/\text{cm}^3$.

27. The method of Claim 19 wherein said added energy is optical energy deposited at each said select location to a penetration depth sufficient to cause electron density in a range of $10^{19}/\text{cm}^3$ to $10^{23}/\text{cm}^3$.

28. The method of Claim 19 wherein the added energy generates further unbound electrons.

29. The method of Claim 19 wherein several different foci correspond to respective said select locations.

30. The method of Claim 19 wherein the source of energy in steps (a) and (b) is a single pulse of optical energy having modulated intensity profile.

31. The method of Claim 19 wherein the deposition of energy in steps (a) and (b) is by a single pulse of optical energy, said single pulse having a first portion depositing energy sufficient to cause unbound electrons in the first absorption volume and a second portion of the single pulse depositing energy at said one or more select locations to cause damage.

32. The method of Claim 19 wherein the added energy of step (b) is at an intensity that is the same or different from the intensity of step (a).

33. The method of Claim 19 wherein a penetration depth of deposited optical energy is smaller than the wavelength of the optical energy.

34. The method of Claim 19 wherein each said select region is essentially defined by a penetration depth in a Z axis direction less than a dimension in the X-Y axis plane of a spot of the deposited energy.

35. The method of Claim 19 wherein said damage of material comprises damage at a surface of the material.

36. The method of Claim 19 wherein said damage of material comprises damage below the surface of the material.

37. The method of Claim 19 wherein the energy is deposited in the presence of an entraining fluid that prevents or at least minimizes re-deposition of material during breakdown.

38. The method of Claim 37 wherein the energy of step (b) is deposited in the presence of an entraining fluid that prevents or at least minimizes re-deposition of material during breakdown.

39. The method of Claim 37 wherein the energy of both steps (a) and (b) is deposited in the presence of an entraining fluid that prevents or at least minimizes re-deposition of material during breakdown.

40. A method of producing one or more features of micrometer size or less in a material comprising generating at least one laser pulse of femtosecond duration or less, and directing said pulse to a material to cause damage in the presence of an entraining fluid that entrains debris caused by such damage.

41. The method of Claim 40 wherein the material has a surface, the pulse is directed to the surface, and the entraining fluid moves along the surface.

42. The method of Claim 40 wherein the entraining fluid is a liquid bath that is essentially quiescent.

43. The method of Claim 40 wherein the entraining fluid is a gas.

44. The method of Claim 43 wherein the gas is moving and exerts a force sufficient to entrain the debris.

45. The method of Claim 40 wherein the entraining fluid is essentially quiescent and has a density sufficient to entrain the debris.

46. The method of Claim 40 wherein the entraining fluid is moving and exerts a force sufficient to entrain the debris.

47. The method of Claim 40 wherein the entraining fluid is water or liquid hydrocarbon.

48. The method of Claim 40 wherein the material is submersed in the fluid.

49. The method of Claim 40 wherein said features are nanoscale features having at least one dimension less than a micrometer.

50. A method of laser induced breakdown (LIB) of a material comprising: generating a pulsed laser beam characterized by a deterministic fluence threshold at which breakdown occurs, providing damage with less than 10% variation of a dimension of features across the material; and selecting a numerical aperture objective for focusing sufficient to define a spot in or on the materials so that LIB causes damage of an area covering less than 50% of the area of the spot; and directing said pulsed beam to a point at or beneath the surface of the material to form features of less than 250 nanometers.

51. The method of Claim 50 wherein the numerical aperture objective is selected to define an area whose dimensions are less than about 160% of the wavelength of the laser light.

52. The method of Claim 50 wherein said laser beam has a wavelength, said ablation forms a feature having a maximum dimension which is in a range of about 1/4 to over an order of magnitude smaller than said wavelength.

53. The method of Claim 50 wherein said feature is 20 nanometers or less.

54. The method of Claim 50 wherein a plurality of features are formed in said material characterized by said variation which is less than 5%.

55. The method of Claim 52 wherein said wavelength is in a range of 350 to 600 nanometers.

56. The method of Claim 52 wherein said wavelength is in a range of 500 to 550 nanometers.

57. The method of Claim 52 wherein said wavelength is 527 nanometers.

58. The method of Claim 50 wherein said pulsed beam comprises pulses having pulse width of a picosecond or less.

59. The method of Claim 50 wherein said pulsed beam comprises pulses having pulse width of 600 femtoseconds.

60. The method of Claim 51 wherein said numerical aperture objective is an oil immersion objective lens.

61. The method of Claim 50 wherein said material is transparent.

62. The method of Claim 50 wherein said material is opaque.

63. The method of Claim 50 wherein said material is biologic.

- 64. The method of Claim 50 wherein said material is tissue.
- 65. The method of Claim 50 wherein said material is glass.
- 66. The method of Claim 50 wherein said material is silicon.
- 67. The method of Claim 50 wherein said material is quartz.
- 68. The method of Claim 50 wherein said material is sapphire.
- 69. The method of Claim 50 wherein said material is metal.
- 70. The method of Claim 50 wherein said feature is 16 nanometers or less.